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ABSTRACT. The isotopic and chemical signatures for ice-age and Holocene ice from Summit, Greenland, and Penny Ice Cap, Baffin Island, Canada, are compared. The usual pattern of low $\delta^{18}O$, high Ca^{2+} and high Cl^- is presented in the Summit records, but Penny Ice Cap has lower than present Cl^- in its ice-age ice. A simple extension of the Hansson model (Hansson, 1994) is developed and used to simulate these signatures. The low ice-age Cl^- from Penny Ice Cap is explained by having the ice-age ice originating many thousands of km inland near the centre of the Laurentide ice sheet and much further from the marine sources. Summit's flowlines all start close to the present site. The Penny Ice Cap early-Holocene $\delta^{18}O$'s had to be corrected to offset the Laurentide meltwater distortion. The analysis suggests that presently the Summit and Penny Ice Cap marine impurity originates about 500 km away, and that presently Penny Ice Cap receives a significant amount of local continental impurity.

INTRODUCTION

The Summit (Greenland) records are used here to represent a typical Northern Hemisphere site whose flow geometry has not changed much over the last 50 kyr. The Summit records are compared to those from Penny Ice Cap, Baffin Island, Canada, whose flowline origin is not so well constrained in the past. Figure 1 shows the locations of the Summit site (72°34′ N, 37°37′ W; 3232 m a.s.l.), Penny Ice Cap (67°15′ N, 65°45′ W; 1900 m a.s.l.) and Barnes Ice Cap, Baffin Island, Canada. The background map of Figure 1 shows the maximum (about 22 kyr BP) reconstructed ice cover of North America (Fisher and others, 1985) assuming a non-deforming bed under Hudson Bay. Figure 2 shows a suite of Summit variables: $\delta^{18}O$ from the Greenland Icecore Project (GRIP) ice core (Johnsen and others, 1997) and the ions, calcium (Ca^{2+}), chlorine (Cl^-) and ammonium (NH_4^+), from the Greenland Ice Sheet Project 2 (GISP2) ice core (Mayewski and others, 1997). Figure 3 shows the same suite of variables from the 1995 Penny ice core (Fisher and others, 1998; Zdanowicz and others, 2000) for the bottom-most 15 m of core. Comparing Figures 2 and 3, it is obvious that Cl provides the major difference in ice-age signatures: Penny Ice Cap has lower Cl for the ice age than for the Holocene, while Summit has much higher Cl in the ice age.

The dashed lines in Figure 1 connecting Keewatin Dome ("KK") to the present position of Penny ("P") and Barnes ("B") Ice Caps are the longest possible flowlines for ice in these two remnant ice masses. With this reconstruction, Fox Dome ("FF") is in fact a long ridge. Down-ridge flow can occur, so such long flowlines are possible.

THE HANSSON MODEL

Since an extended Hansson model is central to these differences, we will now review that model. As Figure 4 shows, continental and marine impurity is thrown into the air with an initial air concentration $C_{\mathrm{air}}(0)$ (kg impurity m^{-3} air), and this is vertically averaged up to the top of the troposphere (thickness H). This initial injection of impurity is reduced mainly by rain precipitation over its lifetime, but finally at high latitudes by snow, which drops a remnant of the original injected amount onto the ice cap. With time t ($t = 0$ being the injection time) the impurity loses mass in proportion to the concentration (see Fig. 4):

$$\frac{\mathrm{d}C_{\mathrm{air}}(t)}{\mathrm{d}t} = -\Psi C_{\mathrm{air}}(t)\,, \qquad (1)$$

which integrates immediately to $C_{\mathrm{air}}(t) = C_{\mathrm{air}}(0)\mathrm{e}^{-\Psi t}$, where Ψ (1/time) is the proportionality rate constant for the given impurity. Ψ is taken as a constant for a given impurity. A more intuitive quantity related to Ψ is survival time $\tau = 1/\Psi$ (units of time), which is specific to the impurity. For example, sea-salt particles tend to be removed faster than small continental-dust particles. The equation for $C_{\mathrm{air}}(t)$ becomes:

$$C_{\mathrm{air}}(t) = C_{\mathrm{air}}(0)\mathrm{e}^{-t/\tau}\,. \qquad (2)$$

Over most of the water/impurity cycle from source to removal, most of the impurity is removed by wet processes.

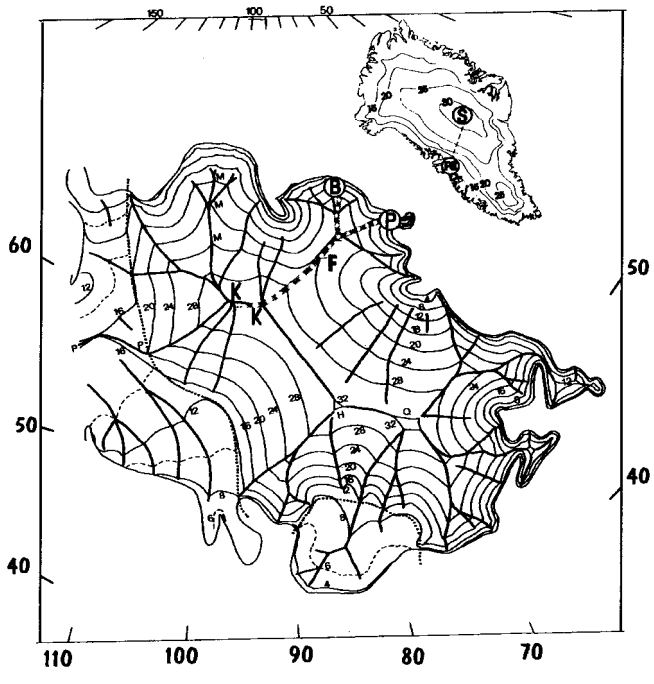

Fig. 1. Map of the reconstructed ice cover over North America at the Last Glacial Maximum (from Fisher and others, 1985) assuming the bed under Hudson Bay is not deforming. The present positions of the Laurentide remnant ice caps, Penny and Barnes, are indicated by a "P" and "B", respectively, and the longest possible flowline to them is shown as the thick gray dashed line joining them to the Keewatin flow centre denoted "KK". The position of the Summit (Greenland) cores is marked "S". Summit is already virtually at the top of the flowline. A flowline from Summit to the west coast of Greenland (Pâkitsoq, "PS") (Reeh and others, 1991) is marked for comparison. Since there is not very much lateral room for expansion of the Greenland ice, the Summit flowline origins must always have been close to the present position.

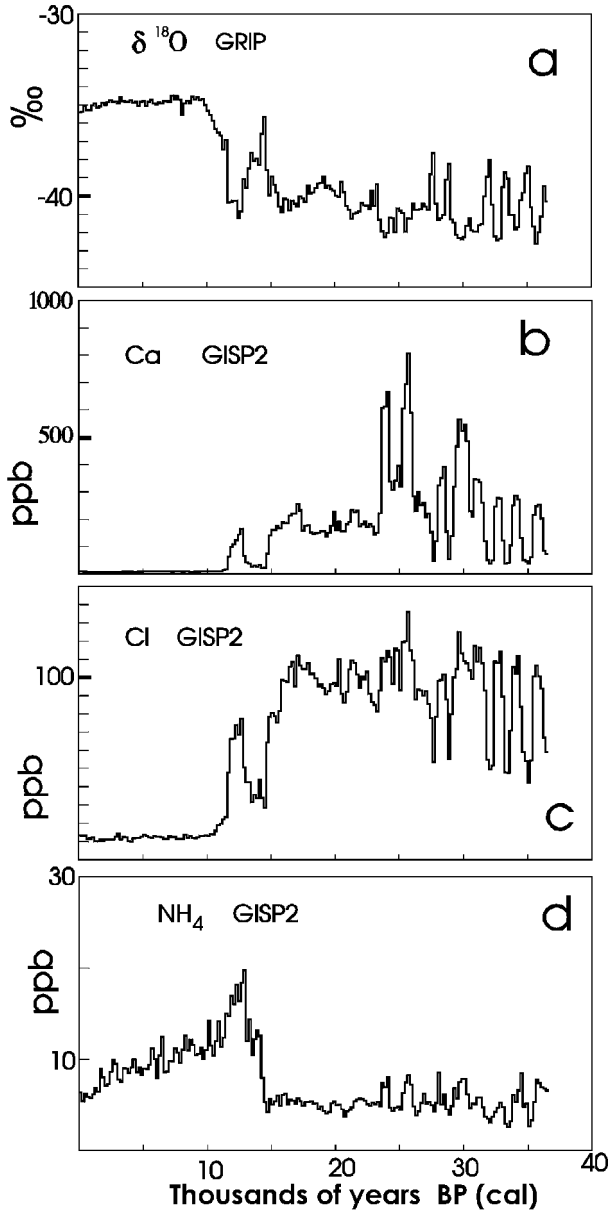

Fig. 2. Summit ice-core records: (a) $\delta^{18}O$ from the GRIP core (Johnsen and others, 1997); (b) Ca^{2+} concentration (ppb) (mass) in GISP2 core (Mayewski and others, 1997); (c) Cl^- concentration (ppb) in GISP2 ice core; (d) NH_4^+ concentration (ppb) in GISP2 core.

Under this wet-process assumption, the survival time is approximated by:

$$\tau = \frac{\rho_{\text{air}}}{\rho_{\text{water}}} \frac{H}{WP} , \tag{3}$$

where H is the active vertical mixing height in the troposphere (about 10 km), P is the average precipitation rate (m water a^{-1}) over the impurity/water cycle, and ρ_{air}, ρ_{water} are standard densities. W, the scavenging ratio, relates the air concentration C_{air} (kg m^{-3}) to the concentration in the precipitation in rain or snow/ice, say C_{ice} (kg impurity (kg^{-1} ice)), i.e.

$$W = \frac{\rho_{\text{air}} C_{\text{ice}}}{C_{\text{air}}} . \tag{4}$$

Over a specific site (on an ice cap), where the accumulation rate is A (m a^{-1}), the impurity flux Φ_{wet} (kg m^{-2} a^{-1}) is:

$$\Phi_{\text{wet}} = C_{\text{ice}} A \rho_{\text{ice}} = C_{\text{air}} AW \frac{\rho_{\text{ice}}}{\rho_{\text{air}}} . \tag{5}$$

In cold, dry places at the end-points of impurity cycles, there is undoubtedly dry fallout, which is not covered explicitly by Equation (5). Because the dry component of ice-cap impurity flux is omitted, the theory underestimates the total flux. However, as discussed below, taking $\Phi_{\text{total}} = \Phi_{\text{wet}}$ is not serious and in any case is what Hansson does.

Rather than try to predict past impurity concentrations and fluxes absolutely by estimating the actual process variables W, C_{air}, A, τ and t_{trans} (total transit time) for each epoch, Hansson (1994) calculates relative concentrations and fluxes using variables relative to the modern ones that are denoted by an asterisk, i.e. W^*, C^*_{air}, A^*, τ^* and t^*_{trans}, Φ^*, C^*_{ice}, A^*, $C^*_{\text{air}}(0)$ and A^*. Thus the relative air concentration comes directly from Equation (2):

$$\frac{C_{\text{air}}}{C^*_{\text{air}}} = \frac{C_{\text{air}}(0)\mathrm{e}^{-t/\tau}}{C^*_{\text{air}}(0)\mathrm{e}^{-t^*/\tau^*}} = \frac{C_{\text{air}}(0)}{C^*_{\text{air}}(0)} \mathrm{e}^{(1-n/k)t^*/\tau^*} , \tag{6}$$

where $n = t/t^*$ is the relative transit time and $k = \tau/\tau^*$ is the relative survival time. Both n and k are species-specific. The relative ice concentration from Equation (4) is:

$$\frac{C_{\text{ice}}}{C^*_{\text{ice}}} = \frac{C_{\text{air}} W}{C^*_{\text{air}} W^*} , \tag{7}$$

and the relative wet flux from Equation (5) is:

$$\frac{\Phi_{\text{wet}}}{\Phi^*_{\text{wet}}} = \frac{C_{\text{air}} WA}{C^*_{\text{air}} W^* A^*} . \tag{8}$$

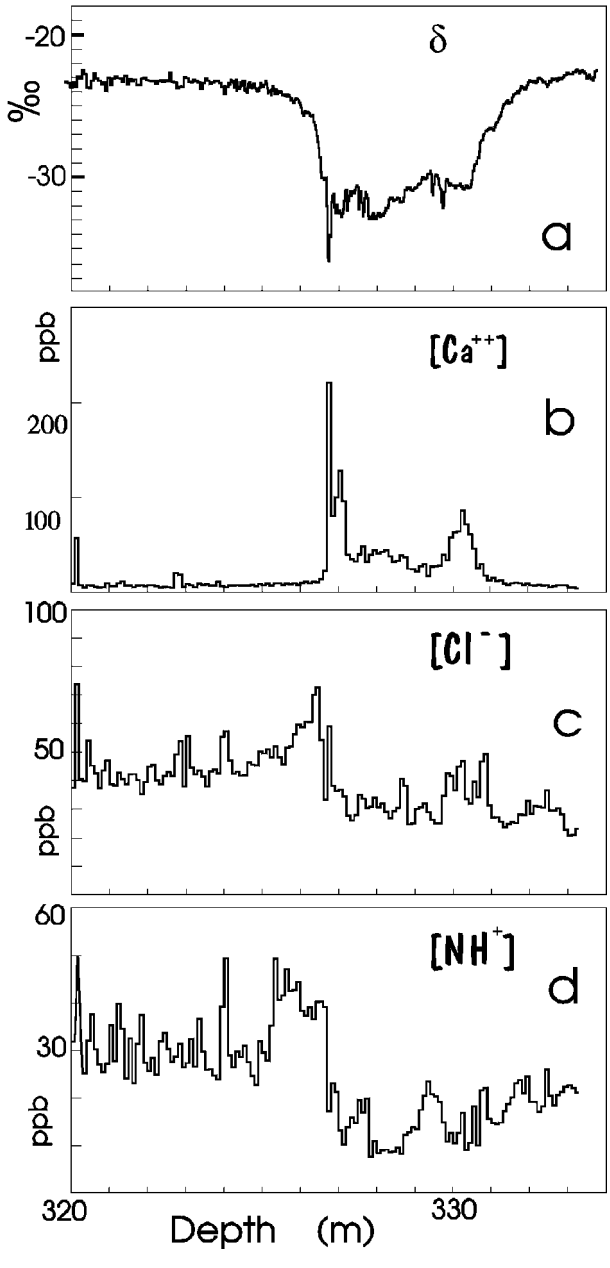

Fig. 3. Penny Ice Cap ice-core records: (a) $\delta^{18}O$ (Fisher and others, 1998); (b) Ca^{2+} concentration (ppb) (mass) (Fisher and others, 1998); (c) Cl^- concentration (ppb); (d) NH_4^+ concentration (ppb).

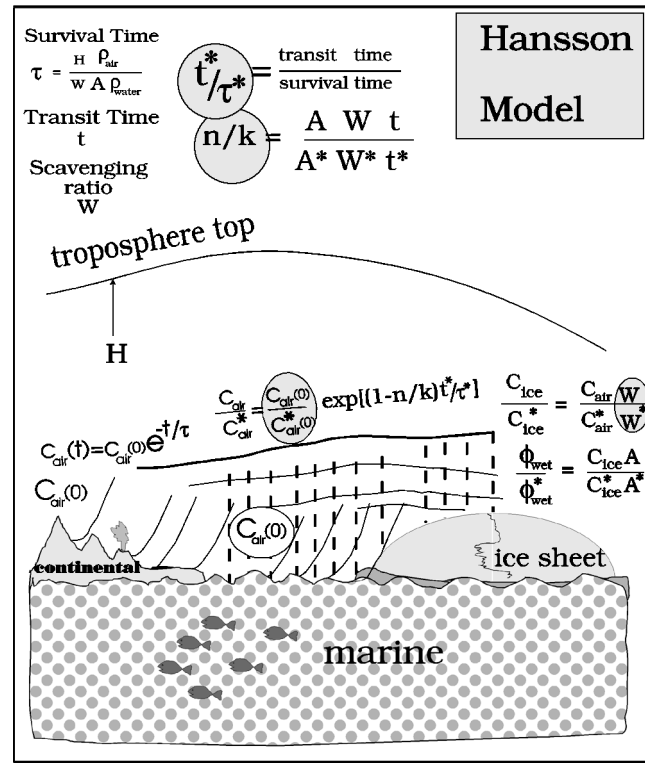

Fig. 4. Cartoon of the Hansson model, relating ice-core geochemical concentration and flux to water-cycle variables and impurity-specific variables. There are two broad input categories of impurity: marine and continental. Asterisks indicate present values.

$$k = \frac{\tau}{\tau^*} = \frac{(\rho_{\mathrm{air}}/\rho_{\mathrm{water}})H/(WP)}{(\rho^*_{\mathrm{air}}/\rho^*_{\mathrm{water}})H^*/(W^*P^*)} = \frac{W^*P^*}{WP} = \frac{W^*A^*}{WA}\,, \tag{9}$$

where it is assumed that

$$\frac{(\rho_{\mathrm{air}}/\rho_{\mathrm{water}})H}{(\rho^*_{\mathrm{air}}/\rho^*_{\mathrm{water}})H^*} = 1\,.$$

The troposphere thickness may have been smaller during colder epochs, but this is offset by the higher air density, so the equation immediately above is not unreasonable. We assume here, as did Hansson (1994), that $W^*/W = 1$.

The Hansson model is largely driven by accumulation rate A at the snow-out site. A in the model comes directly from δ and its relationship to Summit accumulation rates (Fig. 5). There the background assumption is that δ's and accumulation rate in the ice core both depend on site air temperature. A is further assumed to be proportional to the average source-to-site average precipitation rate P. This may work as well as it appears to, because Hansson's model does not explicitly include dry fallout. The site's A is no doubt more variable than the cycle average P, because the high-latitude-site temperatures are more variable than the average temperature over the broad latitude band of the whole water cycle. The model including only wet capture actually simulates the dry in the following manner. Colder periods of time in the ice cores have more negative $\delta^{18}O$, and, as shown below, the site's inferred relative accumulation rate A/A^* is lower. Because the site has a greater temperature variability than the whole water cycle, the change to a cold period is more extreme at the site than for the whole cycle, so that $A/A^* < P/P^*$. From Equations (6–9) we can see that the

USING THE MODEL

Equations (6–8) constitute the Hansson model. In Hansson (1994) n, the relative transit time, is rather insensitive, being presently 1 and during the coldest part of the ice age 0.5, reflecting the idea that increased storminess and higher wind speeds decrease the transit time (Hansson, 1994). This of course assumes the distance from source to site is not changed very much. This was taken as true for all species. The relative survival time $k = \tau/\tau^*$, however, is seen to vary over a much larger range: from the present 1 to about 5 or larger during the ice age (Hansson, 1994). This is because k is largely defined by the accumulation rate over the water/impurity cycle, and that is strongly controlled by the water content of the atmosphere, which is very sensitive to temperature. From Equation (3) we obtain:

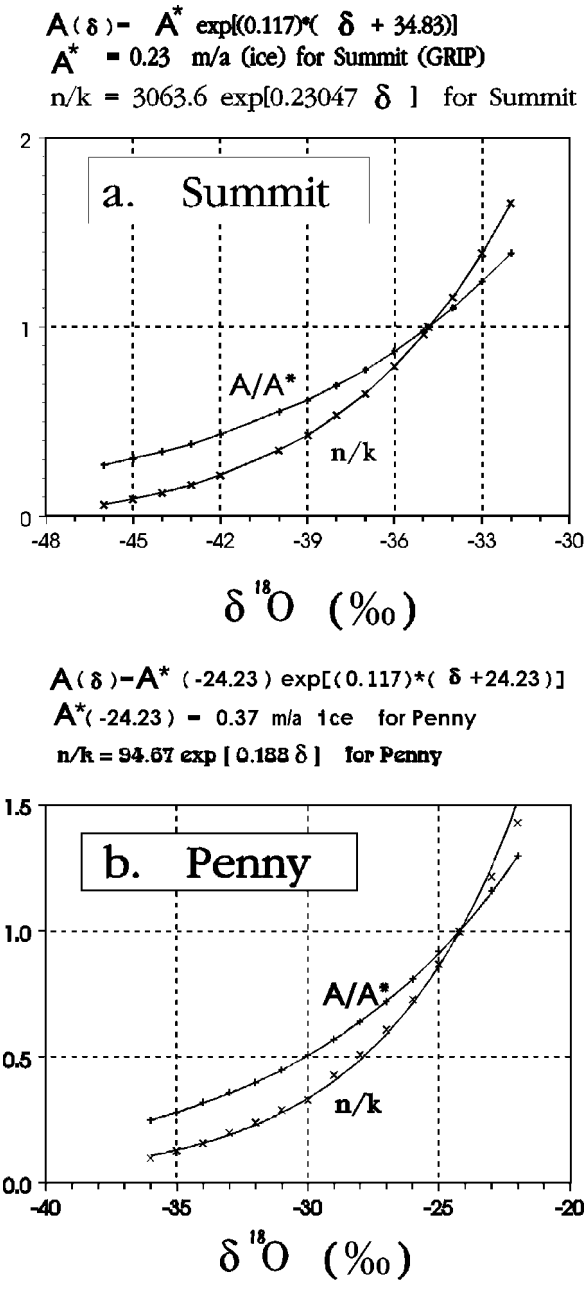

Fig. 5. The past accumulation rate A with respect to present A^* vs $\delta^{18}O$, and the Hansson model variable n/k, where n is the relative transit time, t/t^*, for a given type of impurity and k is the relative survival time, τ/τ^*. Asterisks indicate present values. (a) Measured values for the GRIP core (Dahl-Jensen, 1993); (b) inferred values for the Penny Ice Cap core using the same A–$\delta^{18}O$ relationship.

modeled ice concentrations and fluxes would be too large, because we have used the site accumulations based on the $\delta^{18}O$, which overestimate the cycle temperature swings. This overestimation compensates for this "wet" model's lack of explicit dry fallout, which becomes more important for low-accumulation periods such as the Late-glacial.

Summit site

As mentioned above, the A/A^* relationship comes from the empirical relationship found between $\delta^{18}O$ and the measured annual accumulation rate A (derived from annual layer thickness) for Summit (Dahl-Jensen and others, 1993):

$$A = A^* e^{0.117(\delta - \delta^*)},$$

where $A^* = 0.23$ m ice a^{-1} and $\delta^* = -34.83$‰ are the average modern values. The A/A^* provided above will give k in the model. The value of n is estimated as in Hansson (1994) by assigning $n = 1$ for modern accumulation (i.e. for $\delta^* = -34.83$‰) and $n = 0.5$ for the ice-age ice (i.e. for $\delta^* = -42.00$‰) and linear in between. Thus the key model variables n/k and A/A^* needed for using Equations (6–8) for Summit appear in Figure 5a.

Penny Ice Cap site

The accumulation–$\delta^{18}O$ relationship for Penny Ice Cap is assumed to have the same slope (i.e. $A = A^* e^{0.117(\delta - \delta^*)}$) as Summit, but has different modern averages, i.e. $A^* = 0.37$ m ice a^{-1} and $\delta^* = -24.23$‰. $n = 1$ for modern $\delta^{18}O = -24.23$‰, $n = 0.5$ for the ice-age $\delta^{18}O = -34.00$‰ and linear in between. The Penny Ice Cap n/k and A/A^* functions appear in Figure 5b.

THE DISTANCE FROM SOURCE TO SITE, AND THE EFFECTS ON n/k

In Hansson's model, t is the travel time taken for an impurity to travel from its source to the ice-cap flowline origin, and t^* is the present travel time to the modern ice cap. Thus $n = t/t^*$ is the relative travel time. n is 1 presently and for the Greenland sites only slightly different during the ice age (0.5) because although the storminess was somewhat more extreme the sources were probably a little further away, due to increased sea ice and snow cover.

The early part of the Holocene at high latitudes was the warmest, and saw sea ice and major ice cover retreat most quickly (Koerner and Fisher, 1990; Dyke and others, 1996). For example, during the early Holocene the melt layering was at a maximum on Agassiz Ice Cap, Ellesmere Island, Canada. One would expect travel times to decrease quickly in the early Holocene because the continental and marine sources were suddenly closer then during the ice age. That combined with possible stormier conditions would lead one to expect shorter travel times $n < 1$ during the early Holocene.

During the ice age, the flowline origins for Summit may have been slightly further away, but the source distance may have been 2–3 times removed, because of sea ice and snow cover. For the Penny core ice, whose flowline origins during the ice age are postulated to have been possibly thousands of kilometers from the present site (Fisher and others, 1998), the distance to source, and hence travel time, may have been very much longer, because the site itself has been removed. To allow explicitly for the distance to source being different for sites like Summit and Penny Ice Cap we change the definition of n slightly to:

$$n = \frac{t}{t^*} D,$$

where $D = X/X^*$, X being the distance from the source to the flowline origin for ice of a given age in the core, and t/t^* is the relative travel time for a fixed distance as in the original Hansson model. X^* is the modern distance. This change mainly affects Equation (6), where now n/k is replaced by the slightly augmented version $(n/k)D$:

$$\frac{n}{k} D = \frac{t}{t^*} \frac{A}{A^*} \frac{W}{W^*} D.$$

The variables that determine the model predicted concentrations are: t/t^*, A/A^*, t^*/τ^* and $D = X/X^*$.

Various runs of the model will be made using the above variables. The important variable A/A^* (and the derived

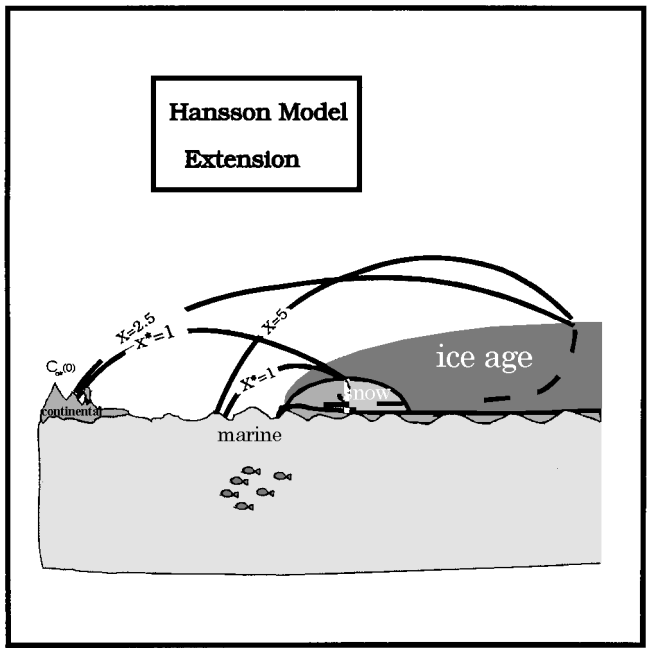

Fig. 6. A cartoon explaining the extension to the Hansson model. X is the average model distance from source to the start of the flowline. X can be changed either by moving the impurity source or by moving the start of the flowline. For Summit the start of the flowline can at most be a few tens of km from the present drill site. For Penny Ice Cap the Late-glacial flowlines could be 2000 km from the present site (see Fig. 1). X^* is the present distance.

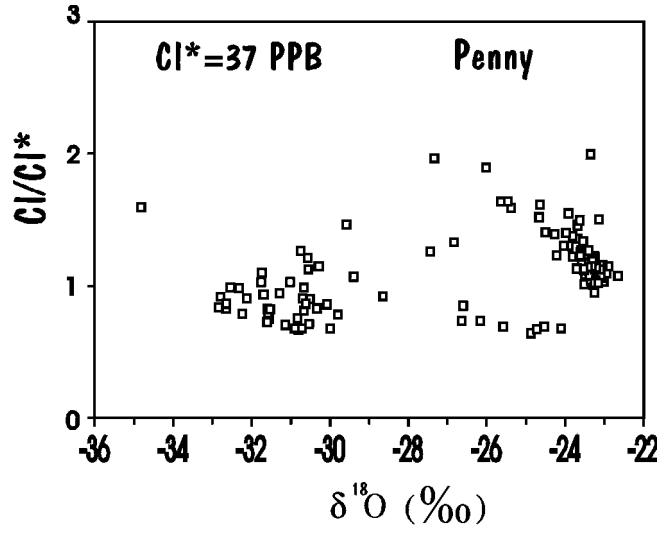

Fig. 7. Penny Ice Cap chlorine vs uncorrected $\delta^{18}O$ for early-Holocene and ice-age ice. The early-Holocene $\delta^{18}O$ values have probably been affected by meltwater from the wasting Laurentide ice cap and consequently need correcting. For corrected version of this figure see Figure 8b.

n/k) will come from the measured $\delta^{18}O$ dependence taken from the Summit core and shown in Figure 5a and b. As before, the (distance constant) relative travel time t/t^* will be 1.0–0.5. The present travel time normalized to the "survival time" of the impurity is very species-specific and we will use the Hansson values as our guide for the marine (Cl^-) and the continental species (Ca^{2+}). In keeping with the simplicity of the Hansson model, D, for Penny Ice Cap, will be a function of the ice-core $\delta^{18}O$, with the maximum being assigned to the most negative ice-age $\delta^{18}O$, and the modern value of 1 to modern $\delta^{18}O$. In between D will vary linearly. The maximum D during the ice age is called DIST in Figures 8 and 9 below. For Summit, DIST is close to 1, because the ice-core site is already within a few tens of km of all the flowline origins for that core (see Fig. 1). In the Penny Ice Cap core, however, DIST depending on the impurity is either about 5 (for marine sources) or 2.5 (for the more remote continental sources) (see Fig. 6). This is because the Penny Ice Cap core flowline origins may have been deep inside the Laurentide ice sheet during the ice age. After extensive experimentation, these were found to be the values that best fit the ($\delta^{18}O$, Cl) and ($\delta^{18}O$, Ca) pairs plots using the series of Figures 2 and 3 for Summit and Penny Ice Cap, respectively.

CORRECTING THE EARLY-HOLOCENE $\delta^{18}O$ FOR ICE-AGE SPIKED SOURCE WATER

Figure 7 presents the Cl/Cl^* vs $\delta^{18}O$ for the Penny Ice Cap core. The relationship between these two would seem to be double-valued, but we suggest that this is due to early-Holocene "$\delta^{18}O$ contamination" of the surface water of the source oceans by fresh low-δ meltwater from the wastage of the Laurentide and Fennoscandian ice sheets (Fisher, 1992). The $\delta^{18}O$ values should be corrected back to a "zero-SMOW (Standard Mean Ocean Water) source ocean" so that the empirical relationships between δ and A are not confused by the meltwater effect. This is, in retrospect, not very important here for the Summit data but has a major effect for the Penny Ice Cap ($\delta^{18}O$, Cl/Cl^*) pairs. The correction comes from examination of the $\delta^{18}O$ and melt-feature record from Agassiz Ice Cap (Fisher and others, 1995) and by examining the elevation-corrected temperature record for the Summit Holocene. Both strongly suggest that the warmest part of the Holocene was the earliest part right after the ice-age termination at 11 550 **BP** (calendar). The Agassiz melt-feature record clearly shows this, whereas the records from all the northern sites have a $\delta^{18}O$ maximum around 7–9 kyr and more negative δ's from that date to the transition. This offset of δ and actual early-Holocene temperature maximum, which is probably caused by the source-water contamination, has been corrected by assuming that the Agassiz δ trend 0–7.5 kyr is continued right back to the early-Holocene maximum suggested by the Agassiz melt-feature trend. The squares in Figure 8b show what happens to the Penny Ice Cap (δ, Cl/Cl^*) data pairs after this correction has been applied to the early-Holocene δ's. The relationship now appears to be single-valued. Similarly, the Summit pairs are given in Figure 8a, but this looks virtually identical to the uncorrected version, because of the shape of the (δ, Cl/Cl^*) relationship. Figure 8 presents the marine-impurity representative Cl, and the continental Ca is given in Figure 9 for both sites.

RESULTS AND DISCUSSION

Running the extended Hansson model as presented using the full range of variables allows one to optimize the model-predicted (δ, Cl/Cl^*) and (δ, Ca/Ca^*) pairs. It was found that the Hansson model in the extended form is needed to produce the "odd" low Cl/Cl^* values for the Penny Ice Cap core and also best fit the Penny Ice Cap continental Ca/Ca^* record.

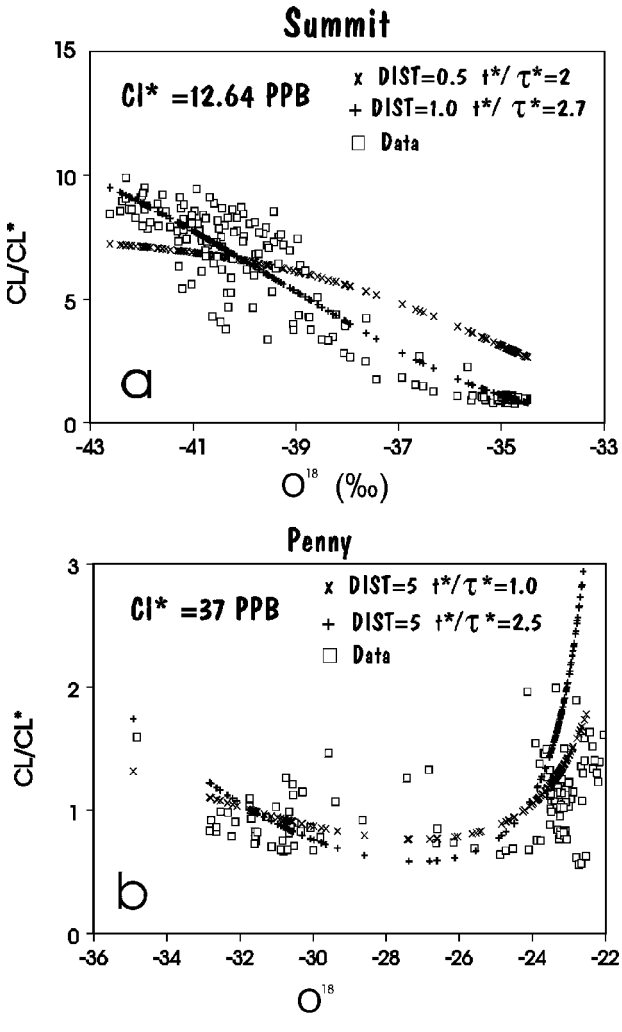

Fig. 8. Measured and modeled relationship between marine-impurity Cl^- and $\delta^{18}O$ for Penny Ice Cap and Summit ice cores. (a) The Summit core results can be fitted best with no significant difference in path length (DIST = 1) and a modern marine transit time 2.7 times the survival time for the injected salts. The Summit marine-impurity concentration in glacial times is 5–10 times the present value. (b) The Penny Ice Cap core results need significantly longer flowlines during the Late-glacial in order to model the lower marine salts during glacial times (i.e. DIST = 5). The modern marine-salt transit time is as above, which is reasonable. Glacial marine concentrations are lower than modern values, which is unique and the starting observation for this whole extension.

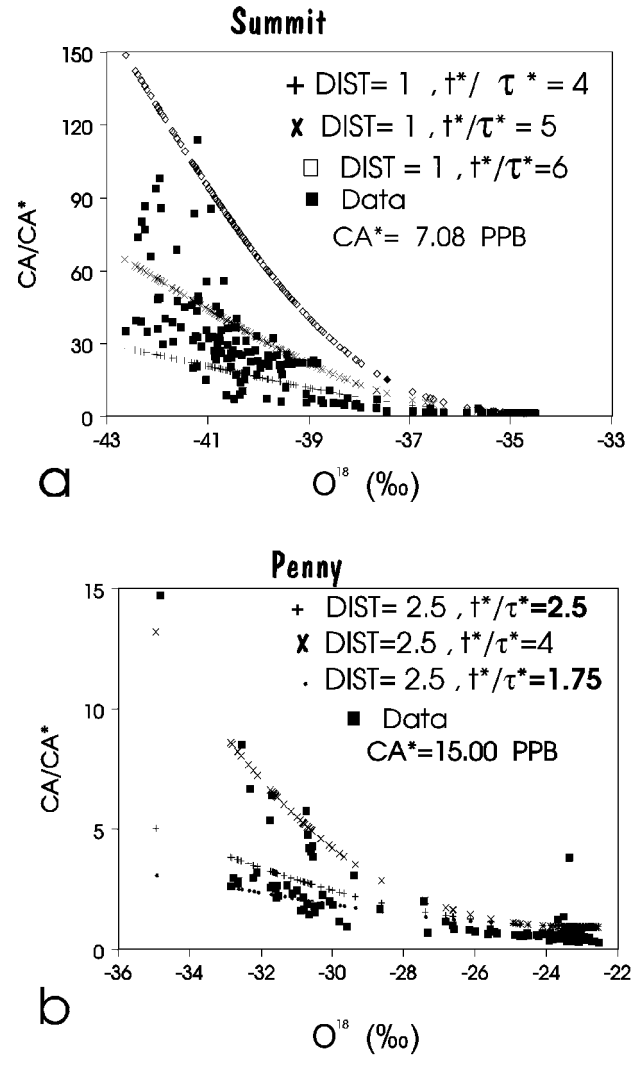

Fig. 9. Measured and modeled relationship between continental-impurity Ca^{2+} and $\delta^{18}O$ for Penny Ice Cap and Summit ice cores. (a) The Summit core results can be fitted best with no significant difference in path length (DIST = 1) and a modern continental transit time 5 times the survival time for the injected impurity. The Summit marine-impurity concentration in glacial times is 30–100 times the present value. (b) The Penny Ice Cap core results need significantly longer flowlines during the Late-glacial in order to model the somewhat higher continental impurity during glacial times (i.e. DIST = 2.5). The modern continental impurity transit time is close to that from Summit, i.e. 1.75–5 times the modern survival time. Glacial continental concentrations are 2–15 times higher than modern values. That the value of DIST is 5 for marine salts and 2.5 for continental impurities is to be expected, because the marine sources, being closer at present, will become relatively much further away from a remote flowline start than a source already very far away (see Fig. 6).

Summit marine

The Summit (δ, Cl/Cl^*) pairs over the last 40 kyr are shown in Figure 8a as squares, and one can clearly see the ice-age Cl is up to 10 times higher than typical Holocene values. Using the A/A^* and n/k functions from Figure 5a, the data pairs can be fit with no significant change in the Summit flowline origin, i.e. DIST = 1, and with a modern marine-impurity relative travel time $t^*/\tau^* = 2.7$. This suggests the marine-impurity source is relatively nearby. DIST = 1 means only that there is not much room to extend the length of the flowline through Summit.

Summit continental

By comparison, the continental-dust indicator, Ca/Ca^* (Fig. 9a), fits best (DIST = 1, as before) with $t^*/\tau^* = 4$–5, suggesting a more remote source for these impurities. The range of Ca/Ca^* variation is much greater, being >60 larger during the last Late-glacial. Both the (δ, marine) and (δ, continental) impurity pairs span about 40 kyr and can be explained with DIST = 1.

Penny Ice Cap marine

Figure 8b shows Cl/Cl^* plotted against δ for glacial and Holocene time. Early-Holocene δs have been corrected, as described above, to remove the early-Holocene surface water Laurentide doping. The A/A^* and n/k functions of the corrected δ are as in Figure 5b. In order for the model

to fit the (δ, marine) data pairs for Penny Ice Cap, DIST = 5 and $t^*/\tau^* = 2.5$. The latter is close to the Summit value, as would be expected for a species-specific constant. DIST = 5 is needed to produce ice-age Penny Ice Cap Cl/Cl*'s smaller than recent ones. All other northern sites have high marine-impurity concentrations in their ice-age ice. One would expect Barnes Ice Cap to share a Penny Ice Cap-like signature (Zdanowicz and others, 2002). This signature, as Figure 6 illustrates, suggests that during the Laurentide maximum (also shown in Fig. 1) the flowline origin for the Penny Ice Cap core ice was 5 times further away from the relatively nearby ocean sources.

This simple addition to the model allows one to estimate the distance to the sources, at least in some first-order sense. Suppose the modern distance to the marine source is denoted, X^*_{marine}. Looking at Figure 1, the highest and furthest origin point for Penny Ice Cap ice would be Keewatin Dome ("KK"), which is about 2000 km from the Baffin Island east coast. During the Glacial Maximum, when the flowline origin was deep inside the main ice sheet, the maximum distance to source would be (X^*_{marine} + 2000) km. So:

$$\text{DIST} = \frac{X}{X^*} = \frac{X^*_{\text{marine}} + 2000}{X^*_{\text{marine}}} = 5\,,$$

and thus $X^*_{\text{marine}} = 500$ km, or about 5° of latitude. This implies the marine source area for the Baffin core sites includes Baffin Bay, Davis Strait, and the northeast Atlantic bounded by Labrador, West Greenland and Newfoundland. This constitutes a relatively local source for sea salts and other marine impurity. The same local sources provide most of the marine impurity for Summit.

Penny Ice Cap continental

The Penny Ice Cap (δ, Ca/Ca*) pairs (Fig 9b) have a more typical Glacial to Holocene signature, with 5–10 times higher Ca in the ice age. The data pairs can be fit with t^*/τ^* between 2.5 and 4 (for Summit it is 4–5) and DIST = 2.5 instead of the marine value of 5. As suggested by Figure 6, this difference in DIST is a geometric effect of the continental sources being much further away. The augmentation of the distance to these sources by the Late-glacial flowlines originating at KK in Figure 1 is the same as for the marine salts, i.e. 2000 km. If the present average distance to modern continental source areas is X^*_{contin} then, as above, the glacial distance is (X^*_{contin} + 2000) km and

$$\text{DIST} = \frac{X}{X^*} = \frac{X^*_{\text{contin}} + 2000}{X^*_{\text{contin}}} = 2.5\,,$$

and thus $X^*_{\text{contin}} = 1333$ km, or about 13° of latitude. This implies the modern source region includes most of eastern and central North America down to latitude 50° and that during the ice age the (X^*_{contin} + 2000) = 3333 km puts the sources >33° of latitude away, as far south as 30° N and well south of the margin of the Laurentide ice sheet. These distances for Penny Ice Cap dust-source areas must be considered minimums, because the Asian sources with X^*_{contin} in the 10 000–20 000 km range were excluded in the above calculation. In fact the Glacial Maximum flowline origins for the Penny Ice Cap would have been geometrically closer to the Asian sources.

A better estimate of X^*_{contin} would come from considering the North American (X^*_{na}) and Asian (X^*_{as}) distances separately, although this introduces more unknown quantities.

$$\text{DIST} = \frac{X^*_{\text{na}} + 2000}{X^*_{\text{na}}} + Wt_{\text{na}} + \frac{X^*_{\text{as}} - 2000}{X^*_{\text{as}}} Wt_{\text{as}} = 2.5\,,$$

where X^*_{na} and X^*_{as} are the present distances to North American and Asian sources and Wt_{na} and Wt_{as} are the Late-glacial relative weights (contributions). If, for the sake of argument, Wt_{na} and Wt_{as} are equal and X^*_{as} is 10 000 km, then X^*_{na} is only about 600 km presently and 2600 km at the Last Glacial Maximum. This seems intuitively too small. This intuitive unease could be remedied with relatively larger contributions of North American sources ending with the first continental example above.

These arguments are very simple and based on a very simple model. That they seem to make simple sense, possibly means that to a first order they and the extended Hansson model are correct.

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